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Tremaine-Weinberg integrals for gas flows in double bars

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Abstract. We report on our attempts to achieve a nearly steady-state gas flow in hydrodynamical simulations of doubly barred galaxies. After exploring the parameter space, we construct two models, for which we evaluate the photometric and the kinematic integrals, present in the Tremaine-Weinberg method, in search of observational signatures of two rotating patterns. We show that such signatures are often present, but a direct fit to data points is likely to return incorrect pattern speeds. However, for a particular distribution of the tracer, presented here, the values of the pattern speeds can be retrieved reliably even with the direct fit.

1. Introduction

Bars within bars are common in disc galaxies – up to 30% of early-type barred galaxies contain them (Erwin & Sparke 2002). It is generally expected that they play a role in the feeding of active galactic nuclei, though the direct theoretical confirmation is difficult, as the interaction between the bars considerably narrows the range of possible systems (Maciejewski & Sparke 2000, hereafter MS00; Maciejewski & Athanassoula 2008). Corsini, Debattista, & Aguerri (2003) demonstrated that in NGC 2903 the two bars rotate with two different pattern speeds. Maciejewski (2006) and Merrifield, Rand, & Meidt (2006) proposed extensions to the Tremaine-Weinberg method (Tremaine & Weinberg 1984) in order to derive multiple pattern speeds. There were also attempts to derive them from direct fitting of straight lines to the Tremaine-Weinberg (TW) integrals. Here we analyse in detail the behaviour of the TW integrals in hydrodynamical models of gas flow in double bars. Since only one dynamically plausible model of double bars has been constructed so far (MS00), we approach the problem from another direction here: by changing the parameters of the two bars, we search for steady-state flows, which may indicate preferred systems.

2. Code and models

We used the grid-based Eulerian hydrodynamical code CMHOG written by James M. Stone and adopted to the polar grid in two dimensions by Piner, Stone, & Teuben (1995). The code implements the piecewise parabolic method

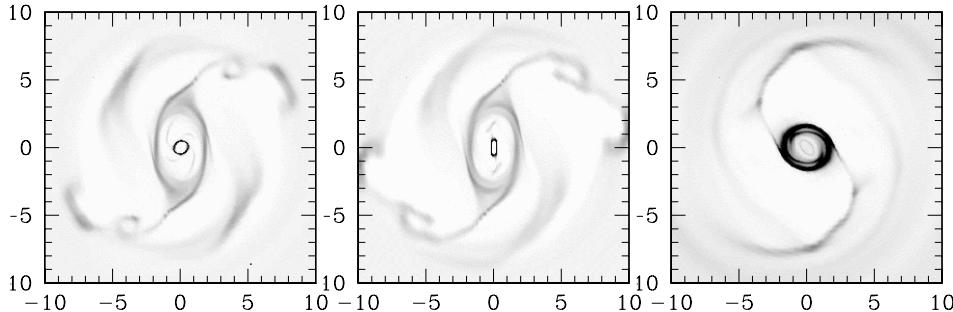


Figure 1. Snapshots of gas density in two models of gas flow in double bars: Setup 1 at 955 Myr (left panel) and at 980 Myr (central panel); Setup 2 at 1445 Myr (right panel). Darker shading indicates higher density. Both bars rotate counterclockwise and the outer bar is vertical on the plots. Units on the axes are in kpc.

(PPM), it uses the isothermal equation of state and it does not account for self-gravity in gas. From the set of models by Regan & Teuben (2003, hereafter RT03) of gas flow in a single bar, we picked the ones in which the flow is likely to become a steady state after the secondary bar is introduced. This is likely if in the single bar the gas settles on an oval around that bar, with no features in the centre, where the secondary bar is going to be placed. The models in RT03, which consider cold gas (5 km s^{-1} speed of sound), are particularly suitable, since for warmer gas a nuclear spiral develops in the centre (Maciejewski 2004).

The model from the bottom-right panel in fig.3 of RT03 (axial ratio of the bar $a/b = 2.0$, bar quadrupole moment $Q_M = 12.5 \times 10^{10} \text{ M}_\odot \text{ kpc}^{-2}$, central mass concentration $\rho_c = 1.0 \times 10^{10} \text{ M}_\odot \text{ kpc}^{-3}$) is the best case of the oval flow around the bar within which the secondary bar can be placed (Setup 1). We also searched for models with the nuclear ring sufficiently large that the flow patterns induced by the secondary bar could fit within it (Setup 2). As the starting point for that setup, we used the models from the top row of fig.3 in RT03 ($a/b = 2.0$, $\rho_c = 3.5$), but in order to increase the size of the nuclear ring, we slowed down the rotation of the bar by increasing its Lagrangian radius r_L (measured at the L1 point) from 6 kpc in RT03 to 11 kpc. In total we constructed 21 models by varying a/b between 1.8 and 2.5, Q_M between 4.5 and 12.5, and ρ_c between 1.0 and 4.8, in the units above. Five out of these 21 models reproduce well the two desired setups described above: gas flows for Setup 1 appear to reach steady-state within the oval flow, but not outside it, while gas flows for Setup 2 are steady-state throughout, although strong shocks persist along the bar.

For the introduction of the secondary bar we used the parameters of the five models above. We constructed 5 models of gas flow in double bars, out of which two closest to the steady-state have the following parameters for Setup 1 (2): $a/b = 1.8(2.0)$, $Q_M = 12.5(5.0)$, $\rho_c = 1.0(3.5)$, $r_L = 6(11)$, in the units above, with the parameters of the inner bar close to those from Model 2 in MS00: the ratio of the semi-major axes 0.2, the mass ratio 0.10 (0.15), the small bar axial ratio 2, and its pattern speed $110 \text{ km s}^{-1} \text{ kpc}^{-1}$. Snapshots of gas density in these two models are showed in Fig.1. The flow in the region of the inner bar in Setup 1 is far from a steady state. A gaseous oval following that bar is flattened

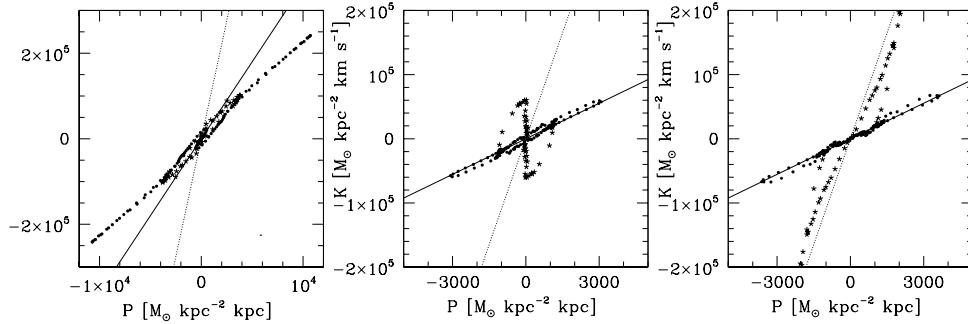


Figure 2. The photometric TW integral P , on the horizontal axis, plotted against the kinematic integral K , on the vertical axis, both measured along the slits parallel to the line of nodes. Stars mark the integrals for the slits offset by less than 2 kpc from the line of nodes (horizontal in Fig.1), while filled circles correspond to the slits further out. The slope of the solid (dotted) line is equal to the imposed pattern speed of the outer (inner) bar. The diagrams are constructed for Setup 1 at 835 Myr (left panel), and Setup 2 at 755 Myr (central panel) and at 1005 Myr (right panel).

when the bars are aligned, and nearly circular at bars perpendicular. This is inconsistent with the orbital structure found in Model 2 of MS00. However, the low central mass concentration in Setup 1 may imply that the x_2 orbital family that gives rise to the orbits supporting the inner bar in Model 2 from MS00 is absent there. Throughout both bars, the gas flow in Setup 1 is likely to follow orbits that originate from the x_1 orbits in a single bar. In Setup 2, most of the gas accumulates in the region dominated by the inner bar and the flow is much closer to the steady-state than in Setup 1 or in Model 2 of MS00 (see Maciejewski et al. 2002).

3. Tremaine-Weinberg integrals for the models with two bars

In the two models described above, we followed the gas flows for 3 Gyr, recording the hydrodynamical variables (density, velocity) on the grid every 5 Myr. Two pattern speeds are imposed in our models, and the flow is often far from a steady state, hence the assumptions of the Tremaine-Weinberg method are violated here. However, even with the assumptions of the method violated, the TW integrals remain well defined, and the hydrodynamical variables that we recorded are sufficient to determine them.

For each setup, we calculated the TW integrals at 600 snapshots in time, and searched for a signal of rotating patterns. As our models evolve, we first introduce the outer bar, and then the inner bar. In the early evolutionary stages, with only the outer bar present, the relation between the TW integrals is linear, having the slope consistent with the imposed pattern speed, despite the flow not being completely settled. Once the secondary bar is introduced in Setup 1, the flow becomes very unsettled, and for the great majority of snapshots no relation between the TW integrals is observed. On rare occasions when there is a linear

relation, its slope is inconsistent with the imposed pattern speeds, and there is no indication of two distinct rotating patterns – see Fig.2, left panel.

In Setup 2, the modifications of the flow in the outer bar caused by the introduction of the inner bar are much smaller than in Setup 1, and two steady flows, generated by the two bars, are being established. In the majority of snapshots, the points in the diagram for the TW integrals gather on two distinct lines (Fig.2, central and right panels). The points for the slits far from the line of nodes, where the outer bar dominates the flow, gather on a line whose slope is consistent with the imposed pattern speed of the outer bar. However, in the early evolution of the model, points for the slits close to the line of nodes gather on a line whose slope can vary with time, and is clearly inconsistent with the imposed constant pattern speed of the inner bar (Fig.2, central panel). This changes later in the run, when both sets of points indicate two correct pattern speeds at most of the snapshots (Fig.2, right panel).

4. Discussion and conclusions

Correct pattern speeds in Setup 2 are recovered only at the late stages of evolution, because by then the majority of gas is accumulated in the region dominated by the inner bar. Earlier in the run, the slits close to the line of nodes sample both flows dominated by the inner and the outer bar. At the end of the run, the contribution from the outer bar is reduced, so that *in the slits close to the line of nodes most of the tracer follows the inner bar*. This is the only gas distribution for which two pattern speeds can be derived with good confidence from a direct fit of straight lines to the TW integrals. Otherwise, the points indicating the TW integrals may gather on two lines, but the slope of the second line may show no relation to the pattern speed of the inner bar. Moreover, for many systems with two pattern speeds, points representing the TW integrals may not gather on any line, as in Setup 1. We conclude that if there is more than one rotating pattern in a galaxy, the direct fits to the TW integrals may provide reliable pattern speeds only for a very specific distribution of the tracer. Fully comprehensive work on this subject will be possible once we know the range of systems with two pattern speeds that are dynamically possible.

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